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A STUDY OF SLIP LINES, STRAIN LINES, AND CRACKS IN METALS UNDER REPEATED STRESS

BY

HERBERT F. MOORE

AND

TIBOR VER

BULLETIN NO. 208

ENGINEERING EXPERIMENT STATION

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A STUDY OF SLIP LINES, STRAIN LINES, AND CRACKS IN METALS UNDER REPEATED STRESS

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A STUDY OF SLIP LINES, STRAIN LINES, AND CRACKS IN METALS UNDER REPEATED STRESS

I. Introduction

1. *Scope of Bulletin and Division of Work.*—Much uncertainty still surrounds the mechanism of the fracture of metals under stress, and the interrelation and significance of such phenomena as slip lines, strain lines, fatigue cracks, and other signs of structural damage to metals furnish fruitful fields of study for the metallographist and the testing engineer. It is hoped that this study will throw some light on these phenomena, and that it may be of value in suggesting further lines for experimental study.

At the University of Technical Sciences at Budapest Dr. Ver has for some time carried on a study of the development of slip lines, strain lines, and cracks in metal subjected to repeated stress. When he came to the University of Illinois as holder of the Jeremiah Smith Scholarship from the Hungarian Board of Education, he planned to carry on this study. His work was done under the general direction of Professor Moore, in charge of the Fatigue of Metals Laboratory, who, in addition to having general oversight of the work, coöperated with Dr. Ver in planning the details of the test specimens, testing machines, and methods of testing. The actual carrying out of the testing was done by Dr. Ver in the Fatigue of Metals Laboratory and in the Metallographic Laboratory of the Department of Chemistry. The two authors collaborated in the drawing of conclusions from the test data. Dr. Ver wrote a very detailed account of the tests and Professor Moore has put this account into its present form as a bulletin of the Engineering Experiment Station.

2. *Acknowledgments.*—Acknowledgment is made of the very valuable help of Mr. S. W. Lyon, Engineer of Tests, and Mr. N. J. Alleman, Associate Engineer of Tests, with the Fatigue of Metals Laboratory of the University of Illinois.

This study has formed part of the work of the Engineering Experiment Station of the University of Illinois, of which Dean M. S. Ketchum is the director, and of the Department of Theoretical and Applied Mechanics, of which Prof. M. L. Enger is the head.

TABLE 1

APPROXIMATE CHEMICAL COMPOSITION AND HEAT TREATMENT OF METALS TESTED

Metal	Content-values in per cent	Heat treatment
Armco Iron..............	Carbon 0.02; Silicon 0.02; Manganese 0.03; Phosphorus 0.005; Sulphur 0.042	Box annealed by manufacturer
0.20 Carbon Steel S.A.E. 1020..................	Carbon 0.20; Manganese 0.45; Phosphorus 0.040; Sulphur 0.045	As rolled by manufacturer
Chrome-Nickel Steel S.A.E. 3135..................	Carbon 0.35; Manganese 0.65; Phosphorus 0.04; Sulphur 0.045; Nickel 1.25; Chromium 0.60	As rolled by manufacturer
Stainless Iron (Ascoloy)....	Carbon 0.09; Silicon 0.06; Manganese 0.03; Chromium 13.0	As rolled by manufacturer
Brass.....................	Copper 60.0; Zinc 40.0	Heated to 1000 deg. F., held 30 min., cooled in air
Monel Metal.............	Copper 28.0; Nickel 67.0; Iron 2.0; Manganese 1.5; Carbon 0.20	As rolled by manufacturer
Duralumin...............	Aluminum 95.5; Copper 3.2; Iron 0.3; Magnesium 0.7; Silicon 0.3	As heat treated and rolled by manufacturer

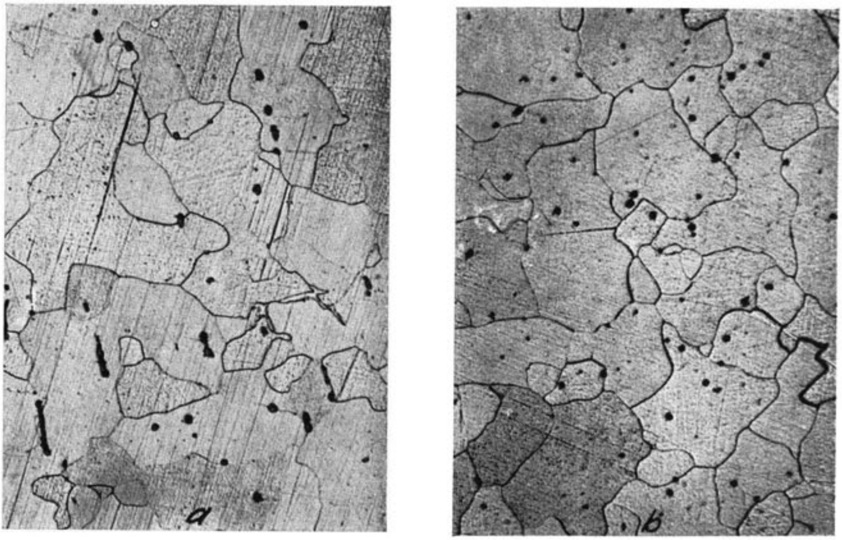
TABLE 2

MECHANICAL PROPERTIES OF METALS TESTED

Metal	Yield Point lb. per sq. in.	Tensile Strength lb. per sq. in.	Elongation in 2 in. per cent	Reduction of Area per cent	Brinell Number
Armco Iron.............	20 500	40 000	42.0	54	76
0.20 Carbon Steel S.A.E. 1020.................	37 000	58 700	36.0	45	107
Chrome-Nickel Steel S.A.E. 3135..........	63 000	102 000	25.0	39	256
Stainless Iron (Ascoloy)..	52 500	87 000	30.0	41	192
Brass..................	18 600	49 000	50.0	24	70
Monel Metal...........	36 600	79 000	47.0	49	126
Duralumin.............	38 500	53 600	18.5	23	103

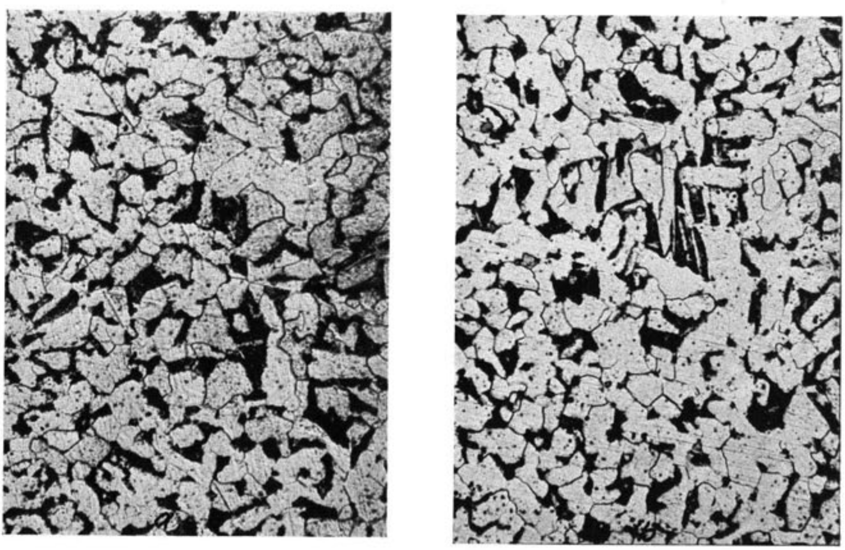
II. MATERIALS, TEST SPECIMENS, AND APPARATUS

3. *Materials.*—The following metals were studied: Armco iron (0.02 per cent carbon), S.A.E. 1020 plain carbon steel (0.20 per cent carbon), S.A.E. 3135 chrome-nickel steel, stainless iron (Ascoloy), brass, monel metal, and duralumin. The approximate chemical compositions and heat treatments are given in Table 1, the mechanical properties in Table 2, and characteristic micrographs for sections along and across the direction of rolling in Figs. 1 to 7, inclusive.



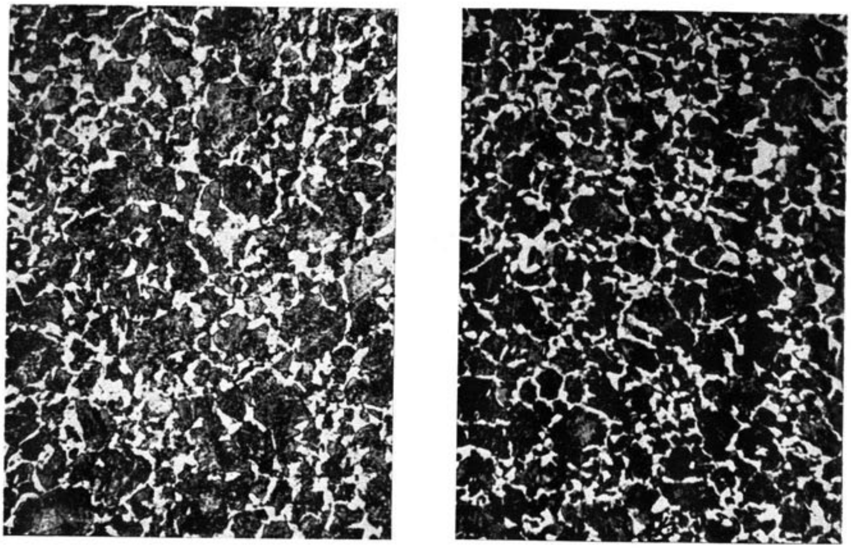
(a) Longitudinal Section (b) Transverse Section

FIG. 1. MICROGRAPHS OF ARMCO IRON (x 188)



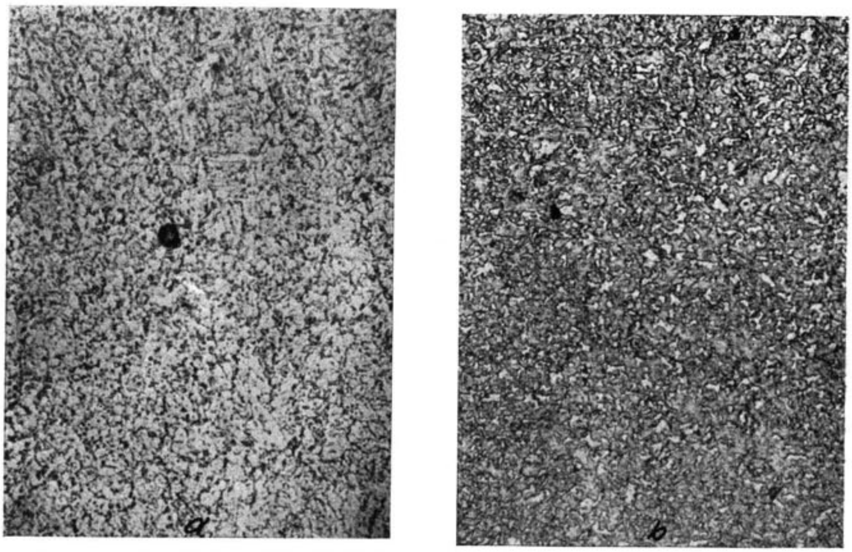
(a) Longitudinal Section (b) Transverse Section

FIG. 2. MICROGRAPHS OF 0.20 CARBON STEEL, S.A.E. 1020 (x 188)



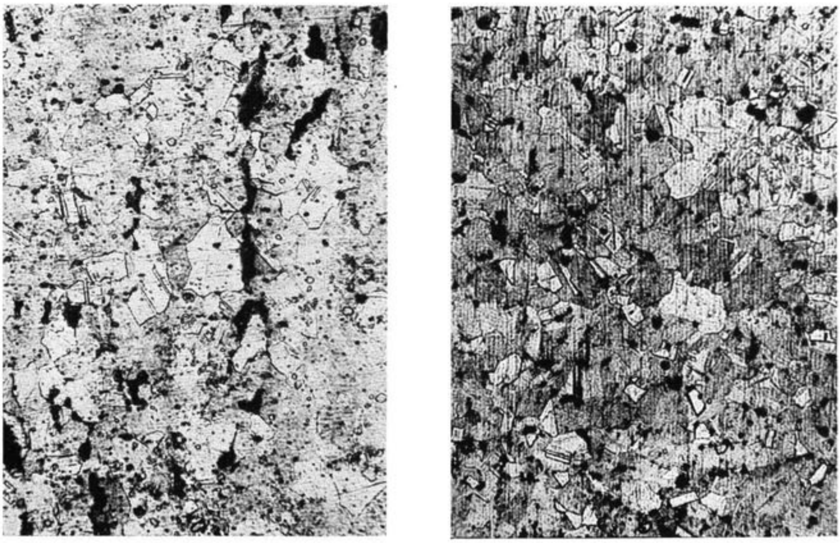
(a) Longitudinal Section (b) Transverse Section

FIG. 3. MICROGRAPHS OF CHROME-NICKEL STEEL, S.A.E. 3135 (x 188)



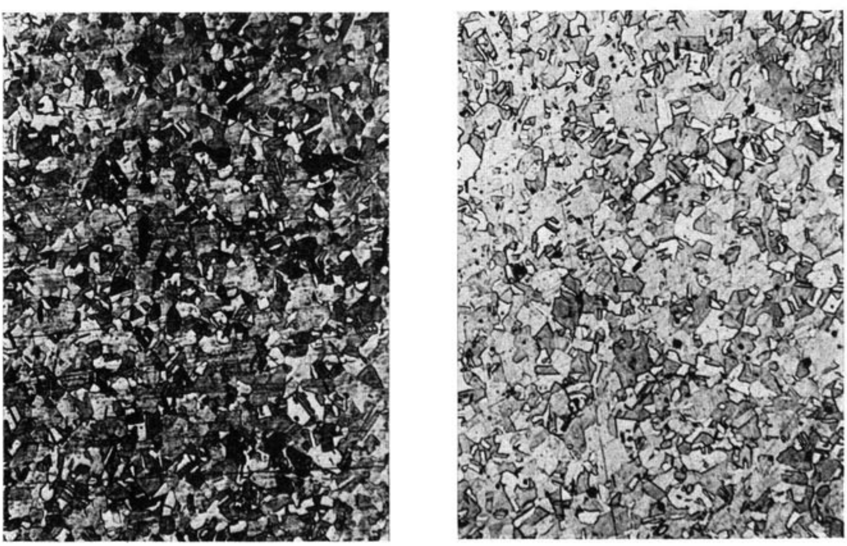
(a) Longitudinal Section (b) Transverse Section

FIG. 4. MICROGRAPHS OF STAINLESS IRON, ASCOLOY (x 188)



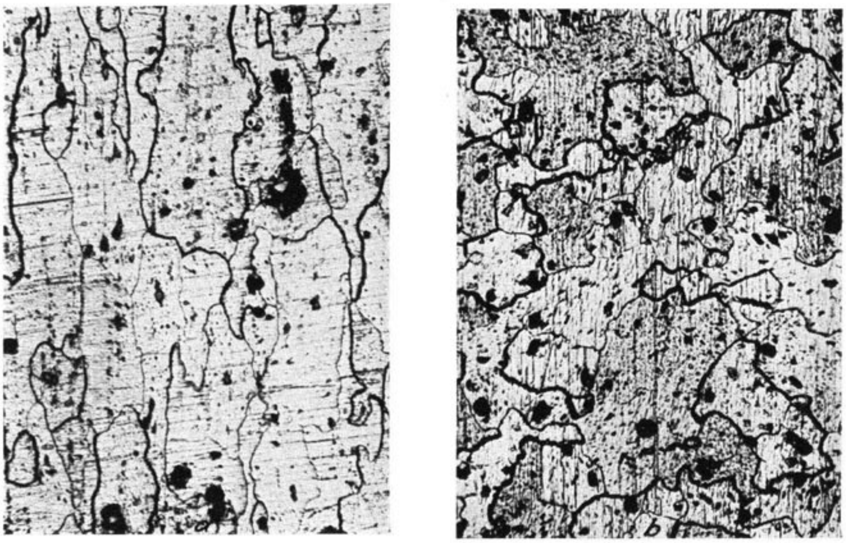
(a) Longitudinal Section (b) Transverse Section

FIG. 5. MICROGRAPHS OF BRASS (x 188)



(a) Longitudinal Section (b) Transverse Section

FIG. 6. MICROGRAPHS OF MONEL METAL (x 188)



(a) Longitudinal Section (b) Transverse Section

FIG. 7. MICROGRAPHS OF DURALUMIN (x 188)

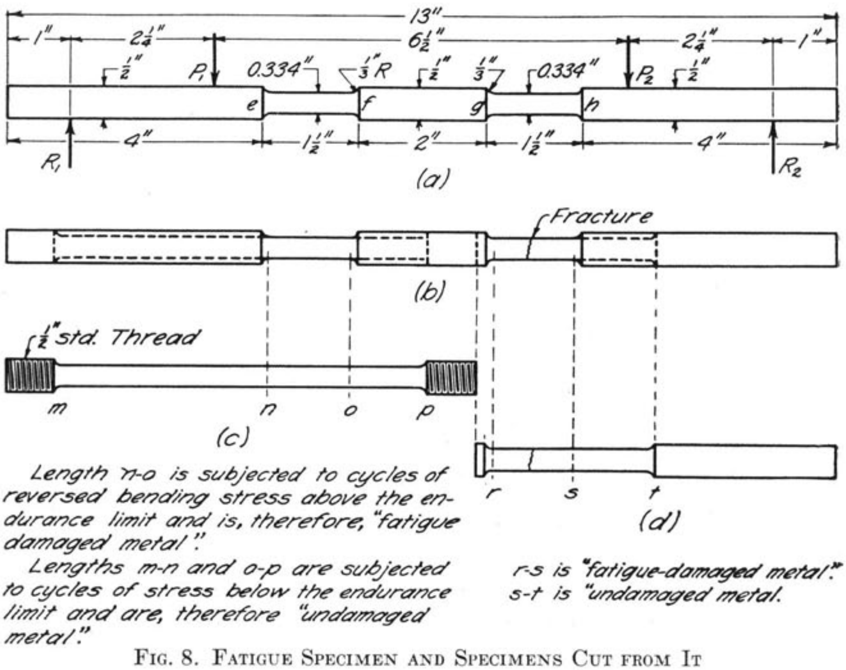


FIG. 8. FATIGUE SPECIMEN AND SPECIMENS CUT FROM IT

4. *Test Specimens.*—All specimens for each metal were cut from one bar. Each specimen was marked with a number indicating the metal tested, and a number indicating the distance in inches of the "near" end of the specimen from the end of the bar. The shape and size of the specimens tested are shown in Fig. 8. Brinell test specimens were short pieces cut from each bar of metal tested.

The specimen for repeated-stress tests is shown in Fig. 8a, and is a rotating-beam specimen. This specimen is different in shape from the rotating-beam specimen commonly used in the University of Illinois laboratories, but was chosen in order that there might be two reduced portions, *ef* and *gh*, subjected to the same intensity of stress. Of course, it is never possible to get the two sections exactly alike in diameter, nor exactly of the same quality of metal, so that fracture always occurred at one reduced section, leaving the other unbroken. However, it seems reasonable to assume that when one reduced section fails the other section has received structural damage (probably in the form of incipient fatigue cracks) from the cycles of stress imposed upon it. In this bulletin the metal so damaged will be called "fatigue-damaged" metal, and the metal in parts of the specimen subjected to lower intensity of stress will be called "undamaged" metal.

After fracture had occurred (or a fatigue crack visible to the unaided eye had formed) the unfractured end of the specimen was turned down to the shape shown by the broken lines in Fig. 8b, and in greater detail in Fig. 8c. This specimen as shown is a tensile specimen, but with unthreaded ends may be used as a torsion specimen. The part *mn* is from metal which, presumably, is undamaged metal, and this is true of the part *op* also. The part *no* is, presumably, from fatigue-damaged metal. Thus it became possible to observe the behavior under various tests of the same metal with and without fatigue damage.

The fractured end of the specimen was turned down to the shape and size shown in Fig. 8d, and Rockwell "B" hardness tests were made on the portion *rs*, which was fatigue-damaged, and also on the portion *st* which was undamaged metal.

The turning down of the fractured specimens was done with extreme care, so as to avoid disturbing the surface of the part in which fatigue damage had been started. The surface of the specimens was polished and etched several times, to remove any surface effect due to machining. Great care was taken to avoid handling the polished and etched surfaces of the specimens, and to avoid any corrosion. They were greased and kept wrapped in soft tissue paper.

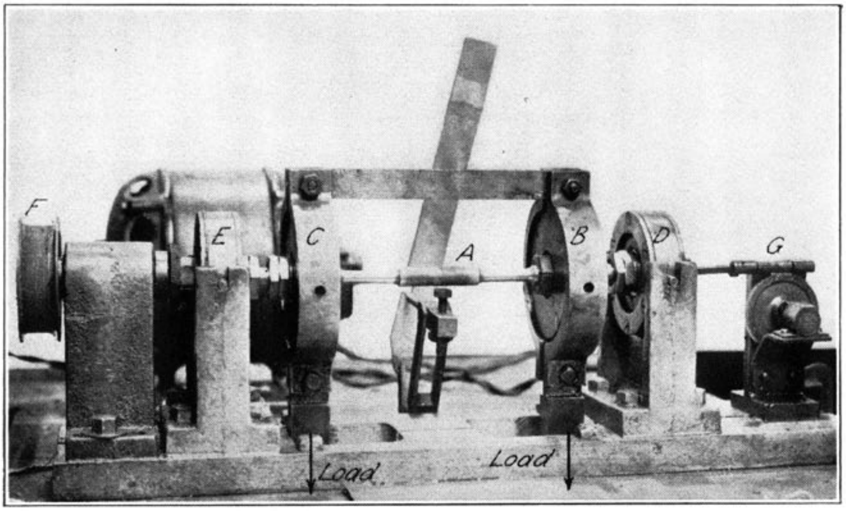


FIG. 9. ROTATING-BEAM TESTING MACHINE USED FOR FATIGUE TESTS

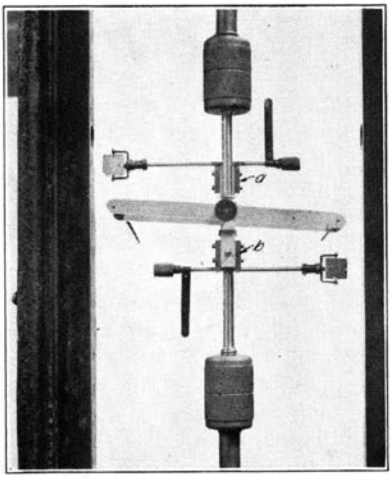


FIG. 10. MARTENS EXTENSOMETER ON TENSILE SPECIMEN

5. *Testing Machines and Strainometers.*—The testing machine for subjecting the specimens to repeated stress was of the Sondericker (or Farmer) type, in which a rotating-beam specimen is subjected to two symmetrically placed transverse loads, giving uniform bending moment between the loads, and subjecting the specimen to cycles of reversed flexure. The machine is shown in Fig. 9, and is a slight

modification of the rotating-beam machine ordinarily used in the University of Illinois laboratories, having the two loads spaced further apart along the specimen. The specimen *A* is held in ball bearings *B*, *C*, *D*, and *E* by means of draw-in collets. It is driven from an electric motor through pulley *F*. Equal loads P_1 and P_2 are applied to the bearings *B* and *C*, by means of weights hung below. The number of revolutions (cycles of stress) is indicated by the counter *G*.

The tensile tests were made on an Olsen 10 000-lb. testing machine, hand driven. Torsion tests were made on a Riehle 10 000-in.-lb. torsion machine of the pendulum type. Brinell tests were made on an Alpha machine, and Rockwell tests on a Rockwell standard machine, made by the Wilson-Maeulen Company.

In the tensile tests the stretch of the test specimen was measured with an Amsler-Martens mirror extensometer, with a gage length of 2 inches. This is shown in Fig. 10.

III. Test Data and Results

6. *Test Data for Repeated-Stress Tests.*—Table 3 gives the test data for the repeated-stress tests on the various metals tested. Figure 11 shows the *S-N* (stress-cycle) diagrams for repeated-stress tests, and Table 4 gives the endurance limits as determined from the test data. As noted on page 13 Rockwell hardness tests were made on the fractured end of nearly every fatigue specimen tested. These tests constituted a hardness survey of the surface both of metal in which fatigue cracks had started and of metal in which fatigue cracks had not started. Table 5 gives the average values of Rockwell "B" hardness (100 kg. load) for metal with and without fatigue cracks. The complete data for this hardness survey are preserved in the files of the Fatigue of Metals Laboratory.

In nearly all the fatigue tests, except those of chrome-nickel steel specimens, the fracture occurred at some distance from the junction of fillet and straight portion of specimen. This junction is the point of theoretical maximum stress, on account of the stress concentration in the fillet. The chrome-nickel steel specimens broke at the junction of fillet and straight portion, illustrating the sensitiveness of chrome-nickel steel to stress concentration.

7. *Tensile Test Data.*—After the fatigue test the unfractured end of each specimen was turned down to the shape of the tension specimen shown in Fig. 8b and 8c. In 1¼ inches of each specimen fatigue damage had, presumably, taken place, while the remainder of the

TABLE 3

TEST DATA OF REPEATED-STRESS TESTS ON ROTATING-BEAM SPECIMENS

Metal	Specimen No.	Stress in Extreme Fibers lb. per sq. in.	Number of Cycles of Stress for Fracture	Remarks
Armco Iron..........	9– 26	32 800	18 700	
	9– 13	28 200	121 000	
	9– 0	26 900	142 000	
	9– 39	26 400	257 800	
	9–104	23 600	1 007 700	
	9– 65	23 900	1 278 700	
	9– 78	22 800	1 406 600	
	9–117	22 800	1 896 700	
	9– 91	22 400	4 775 800	
	9– 52	21 600	10 360 600	Specimen did not fracture
		23 000	1 985 700	Stress raised, no fracture
		24 600	1 373 500	Stress raised, specimen fractured; fatigue strength raised by understressing
0 20 Carbon Steel S.A.E. 1020........	28– 52	35 500	202 900	
	28– 26	27 600	482 300	
	28– 78	29 000	827 200	
	28– 13	26 100	1 116 500	
	28– 39	27 000	1 889 300	
	28– 65	25 200	4 766 300	
	28–104	25 400	10 352 400	Specimen did not fracture
		27 100	1 084 000	Stress raised, specimen fractured
	28– 0	24 000	10 506 000	Specimen did not fracture
		25 400	10 582 000	Stress raised, no fracture
		27 000	2 103 000	Stress raised, no fracture
		28 600	591 800	Stress raised, specimen fractured
	28–117	23 600	10 681 600	Specimen did not fracture
		25 200	6 247 000	Stress raised, no fracture
		26 700	3 610 000	Stress raised, no fracture
		28 200	2 456 300	Stress raised, specimen fractured
	28–147	24 800	5 169 000	
	28–190	24 000	30 779 000	Specimen did not fracture
	28–134	21 500	30 546 400	Specimen did not fracture
	28–177	18 600	30 047 000	Specimen did not fracture
Chrome-Nickel Steel S.A.E. 3135........	27– 91	57 800	78 700	
	27–117	52 000	126 000	
	27– 13	45 700	334 400	
	27– 65	43 400	942 800	
	27– 39	41 400	10 323 000	Specimen did not fracture
		42 900	10 120 000	Stress raised, no fracture
		44 500	10 424 000	Stress raised, no fracture
		46 100	10 537 000	Stress raised, no fracture
		47 700	10 934 500	Stress raised, no fracture
		49 200	2 132 800	Stress raised, specimen fractured
	27–104	40 100	10 423 500	Specimen did not fracture
		41 700	2 649 000	Stress raised, no fracture
		43 200	2 272 000	Stress raised, no fracture
		44 700	2 010 000	Stress raised, no fracture
		46 300	2 000 000	Stress raised, specimen fractured
	27– 26	38 400	10 820 000	Specimen did not fracture
		39 900	10 376 000	Stress raised, no fracture
		41 500	10 000 000	Stress raised, no fracture
		43 000	10 544 000	Stress raised, no fracture
		44 500	10 240 000	Stress raised, no fracture
		46 000	1 777 500	Stress raised, specimen fractured

TABLE 3 (*Concluded*)

TEST DATA OF REPEATED-STRESS TESTS ON ROTATING-BEAM SPECIMENS

Metal	Specimen No.	Stress in Extreme Fibers lb. per sq. in.	Number of Cycles of Stress for Fracture	Remarks
Chrome-Nickel Steel S.A.E. 3135 (*Cont'd.*)	27–130	38 400	9 998 600	Specimen did not fracture
		39 900	10 361 600	Stress raised, no fracture
		41 500	2 545 600	Stress raised, no fracture
		43 000	2 025 400	Stress raised, no fracture
		46 000	2 218 000	Stress raised, no fracture
		47 500	1 374 000	Stress raised, specimen fractured
	27– 78	38 800	10 014 500	Specimen did not fracture
		40 200	10 267 600	Stress raised, no fracture
		41 800	749 500	Stress raised, no fracture
Stainless Iron (Ascoloy)..........	29– 39	57 900	53 300	
	29– 13	54 600	69 200	
	29– 26	56 900	76 800	
	29– 52	53 800	146 000	
	29– 78	47 600	404 200	
	29– 65	46 500	1 582 900	
	29– 91	44 700	8 917 000	Specimen did not fracture
		46 400	1 875 000	Stress raised, no fracture
		48 000	1 627 000	Stress raised, no fracture
		49 600	992 900	Stress raised, specimen fractured
	29– 0	41 600	9 562 000	Specimen did not fracture
		43 400	2 016 000	Stress raised, no fracture
		45 000	1 892 900	Stress raised, no fracture
		46 600	2 145 000	Stress raised, no fracture
		48 200	2 758 800	Stress raised, no fracture
		49 800	1 107 400	Stress raised, specimen fractured
Brass................	108– 52	23 200	642 000	
	108– 78	24 200	676 000	
	108– 0	22 900	903 000	
	108– 65	20 800	1 214 000	
	108– 26	20 600	7 302 700	
	108– 39	21 000	34 075 000	Specimen did not fracture
Monel Metal.........	115– 78	43 600	113 000	
	115– 13	40 500	306 300	
	115– 52	39 300	405 600	
	115– 65	38 900	1 144 500	
	115– 39	36 600	2 310 400	
	115– 26	34 200	7 590 000	
	115–117	34 100	8 680 700	
	115– 0	28 700	103 346 500	Specimen did not fracture
Duralumin...........	130– 65	29 000	317 000	Specimen did not fracture
	130– 91	26 600	628 000	
	130– 13	25 700	1 139 000	
	130– 39	23 200	1 737 700	
	130–117	19 600	4 228 000	
	130– 52	20 200	5 573 000	
	130–104	17 300	11 282 100	
	130– 26	18 300	21 480 000	Specimen did not fracture
		20 600	2 624 000	Stress raised, specimen fractured

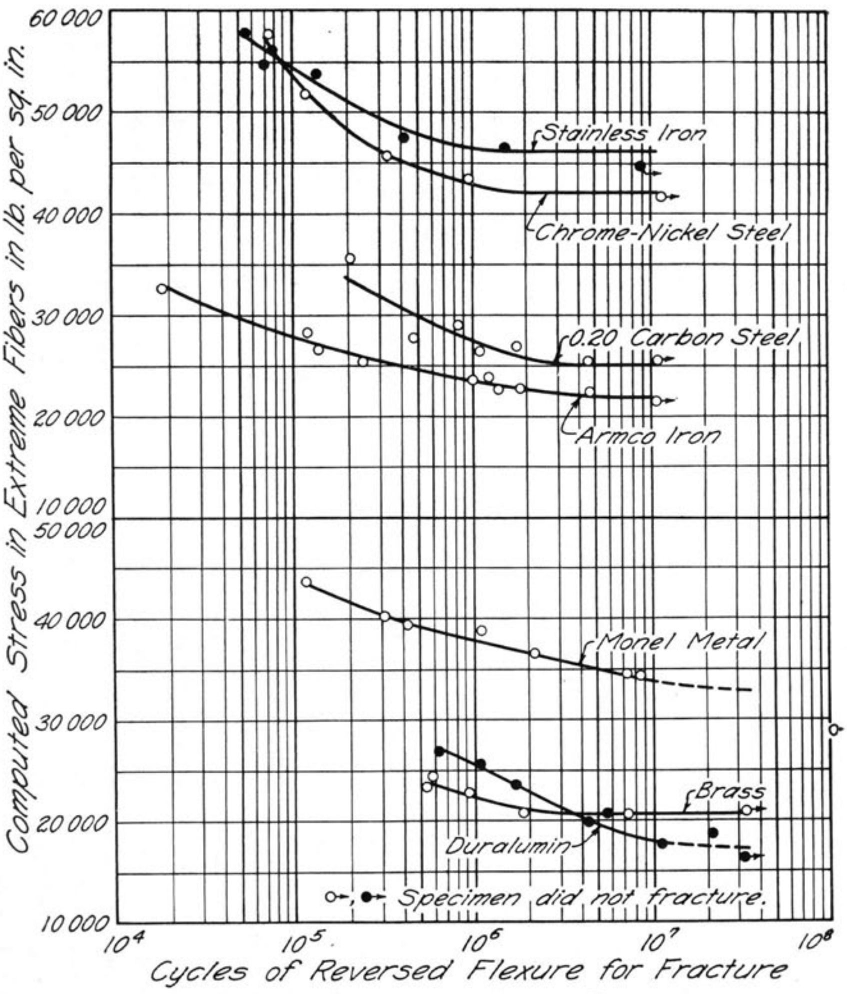


FIG. 11. S-N DIAGRAMS FOR METALS TESTED

length was undamaged metal. Tensile tests to determine the elastic strength of the cracked and uncracked portions were made, using an Amsler-Martens extensometer attached as shown in Fig. 12. The part A of the extensometer spans a gage length half of which (ab) is on metal which has developed fatigue cracks and half of which (bc) is on metal which has not developed fatigue cracks. The part B spans a gage length on metal which has not developed fatigue cracks. It should be noted that the arrangement shown is unsuitable for deter-

TABLE 4

ENDURANCE LIMITS OF METAL TESTED

Rotating-beam testing machine used (Fig. 9) giving cycles of completely reversed bending stress. Test specimen is shown in Fig. 8a. *S-N* (stress-cycle) diagrams are shown in Fig. 12.

Metal	Endurance Limit lb. per sq. in.	Remarks
Armco Iron	22 000	
0.20 per cent Carbon Steel S.A.E. 1020	25 000	
Chrome-Nickel Steel S.A.E. 3135	42 000	
Stainless Iron (Ascoloy)	46 000	
Brass	20 500	
Monel Metal	33 000	Estimated from *S-N* diagram
Duralumin	18 000	Estimated from *S-N* diagram

TABLE 5

HARDNESS TESTS OF METAL WITH AND WITHOUT FATIGUE CRACKS

The Rockwell "B" test was used (1/16-in. steel ball, 100 kg. load). Each value is the average of 60 or more determinations.

Metal	Rockwell "B" Hardness Number	
	Fatigue-damaged Metal *rs*, Fig. 8d	Undamaged Metal *st*, Fig 8d
Armco Iron	29.7	17.9
0.20 per cent Carbon Steel S.A.E. 1020	60.1	55.1
Chrome-Nickel Steel S.A.E. 3135	90.5	89.4
Stainless Iron (Ascoloy)	84.1	84.8
Brass	15.8	13.3
Monel Metal	67.4	66.7
Duralumin	55.5	56.4

mining modulus of elasticity, because the measurements of stretch were not along the same length on the two sides of the specimen.

For all the metals, except the chrome-nickel steel and the 0.20 carbon steel, the first indication of yield was shown in the undamaged part of the specimen (*mn*, Fig. 8c). Complete data of these tests are preserved in the files of the Fatigue of Metals Laboratory.

After the extensometer tests the tension specimens were subjected to further tensile stress until distinct elongation and reduction of area of cross-section were noted. Under loads producing various percent-

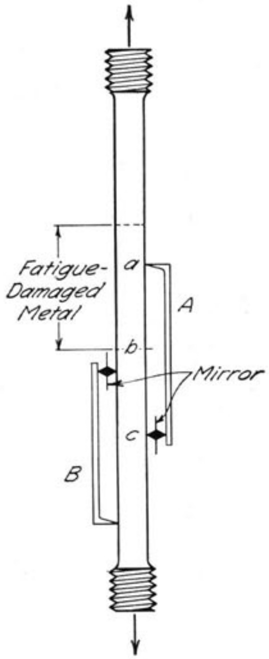


FIG. 12. ATTACHMENT OF EXTENSOMETER FOR TESTS OF FATIGUE-DAMAGED METAL AND UNDAMAGED METAL

ages of elongation the reduced diameter was measured both for the fatigue-damaged part of the specimen and for the undamaged part. Figure 14 shows, to an exaggerated scale, the change of diameter for the fatigue-damaged and for the undamaged parts of specimens of the various metals tested. Table 7 gives average values of reduction of area after different elongations both for fatigue-damaged and for undamaged metal. Complete data for these reduction of area tests are preserved in the files of the Fatigue of Metals Laboratory.

During the progress of the repeated-stress tests and the tensile and torsion tests made on specimens which had been subjected to repeated stress numerous micrographs and macrographs were taken. From these micrographs and macrographs it was possible to study the formation of slip lines, strain lines, and fatigue cracks. The figures beginning with Fig. 15 show these micrographs and macrographs.

IV. Discussion of Results

8. *Hardness of Fatigue-Damaged Steel.*—An examination of Table 5 indicates that the metals studied may be divided into two groups.

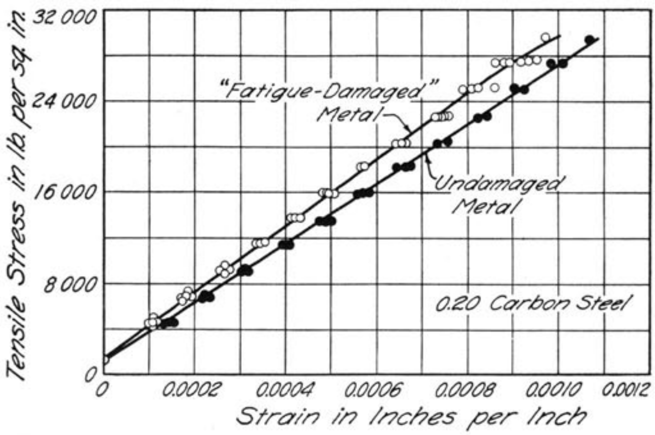


FIG. 13. ELASTIC STRETCH OF FATIGUE-DAMAGED METAL AND OF UNDAMAGED METAL

In the first group may be placed those metals which show a distinct increase of Rockwell "B" hardness after fatigue damage has taken place. This group included Armco iron and 0.20 carbon steel. The remaining metals show either a very slight increase in hardness or a slight decrease.

9. *Effect of Fatigue Damage on Elastic Strength.*—It will be noted that in nearly all cases the undamaged portion of a tensile specimen (*mn*, Fig. 8c) showed signs of plastic yield at a lower load than did the fatigue-damaged part. This indicates a slight increase in elastic strength due to fatigue damage which has not progressed to fracture, although it is not possible even to estimate the amount of such increase. Such an effect is, quite probably, due to cold working, which under cycles of *reversed* stress may set up considerable back-and-forth slip in the metal without an appreciable permanent distortion in either direction.

In tests of specimens of 0.20 carbon steel the elastic stretch of the fatigue-damaged portion was compared with that of the undamaged portion. The simultaneous measurement of elastic stretch of the two portions was made by means of a Martens 2-in. extensometer, and an Olsen 2-in. extensometer calibrated to agree with the readings of the Martens instrument. The fatigue-damaged portion showed a slightly higher modulus of elasticity than the undamaged portion. Figure 13 shows a stress-strain diagram.

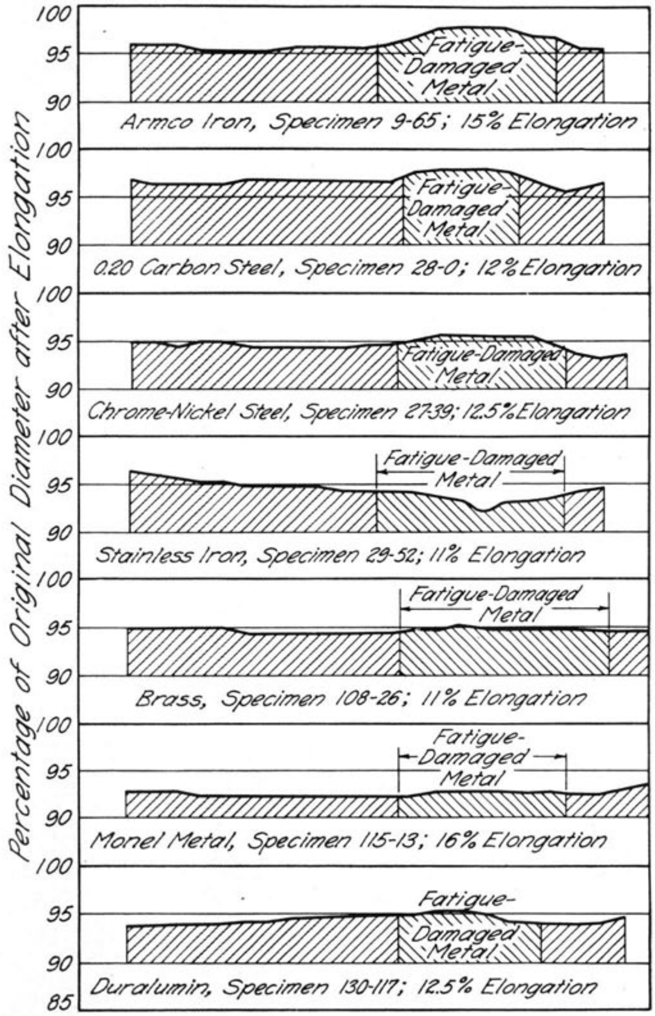


FIG. 14. REDUCTION OF AREA OF FATIGUE-DAMAGED METAL AND OF UNDAMAGED METAL

10. *Reduction of Area of Fatigue-Damaged Metal.*—Examination of Table 6 and of Fig. 14 indicates that the reduction of area under tensile stress above the yield point is distinctly reduced for fatigue-damaged metal. The exceptions to this conclusion are duralumin and monel metal, which show very little change in reduction of area between fatigue-damaged and undamaged metal, and stainless iron which shows an *increase* of reduction of area for fatigue-damaged

TABLE 6

REDUCTION OF AREA UNDER TENSION OF SPECIMENS WITH AND WITHOUT FATIGUE CRACKS

Average values from 3 or more specimens for each metal

Metal	Reduction of Area—per cent					
	Elongation of Specimen (Fig. 8c) of Approximately 5 per cent		Elongation of Specimen (Fig. 8c) of Approximately 10 per cent		Elongation of Specimen (Fig. 8c) of Approximately 20 per cent	
	Part (*mn*) Un-damaged	Part (*no*) Fatigue-damaged	Part (*mn*) Un-damaged	Part (*no*) Fatigue-damaged	Part (*mn*) Un-damaged	Part (*no*) Fatigue-damaged
Armco Iron................	7.2	4.7	14.0	8.5	22.0	13.0
0.20 per cent Carbon Steel S.A.E. 1020..............	7.1	5.6	12.0	9.0	19.0	11.7
Chrome-Nickel Steel S.A.E. 3135.....................	6.3	5.3	11.2	9.0	....	....
Stainless Iron (Ascoloy).....	....	....	9.8	12.5	....	....
Brass......................	....	....	10.2	9.7	....	....
Monel Metal...............	....	....	9.0	8.3	....	....
Duralumin.................	6.5	5.0	9.8	10.0	....	....

metal, but for which there are comparatively few test data. This smaller reduction for fatigue-damaged metal seems logical in view of the fact that fatigue damage may be regarded as the formation of incipient cracks, which would produce the same effect as grooves or nicks in the specimen. The further investigation of reduction of area (or possibly the result of the Kinzel bend test*) as an indicator of endurance limit for short time tests seems a field of some promise. The present test results indicate that fatigue cracks do diminish ductility, but whether an appreciable diminution of ductility is brought about in the early stages of formation of fatigue cracks is a question requiring further experimental study.

11. *Slip Under Repeated Stress.*—The phenomenon known as slip in metals seems to be closely associated with the plastic flow, which, when it becomes appreciable, marks the passing of the limit of elastic strength of a metal. Slip is indicated to the metallographist by the appearance of fine lines across the faces of crystalline grains, and these lines are known as "slip lines" or "slip bands." The specimens of the

*See 1929 Report of Committee E-1 on Methods of Testing, American Society for Testing Materials, Report of Section on Bend Testing.

form shown in Fig. 8c, when polished and etched, were especially adapted for the comparative study of slip lines in metal in which (presumably) fatigue damage had taken place (*no*, Fig. 8c) and in undamaged metal (*mn*, Fig. 8c). All the metals tested, with the exception of stainless iron, were so studied.

In general, it was noted that for stresses above the endurance limit slip lines developed more abundantly in those specimens subjected to a few cycles of high stress than in specimens subjected to many cycles of stress but little above the endurance limit. Under cycles of stress below the endurance limit slip lines were not detected for brass, monel metal, or duralumin, but were very clearly observed on specimens of armco iron and of 0.20 carbon steel.

Slip lines, whether developed by a single test or by cycles of repeated stress, are approximately straight lines, having a particular direction for any grain. As shown by Gough and his associates, this direction is probably associated with the orientation of the atoms in the space lattice of a given grain.* Figure 15 shows typical slip line developments for Armco iron, Fig. 16 those for 0.20 carbon steel, Fig. 17 those for chrome-nickel steel, Fig. 18 those for brass, and Fig. 19 those for monel metal. In some cases, under cycles of reversed bending, slip lines developed in two directions in the same grain. This is shown for Armco iron in Fig. 20 (note the grain in the center of the cut), and for duralumin in Fig. 21.

A somewhat detailed study of the direction of slip lines, and the relation of that direction to the direction of maximum stress, was made by means of repeated-stress tests followed by tests under static tension or static torsion. In general, the direction of slip lines developed under cycles of reversed bending was in the same direction as those developed under static tension. The slip lines (or rather bands) developed under repeated stress were broader than those developed under static tension. This is illustrated in Figs. 22 and 23. These two figures also show how the static tension following the cycles of repeated stress extended existing slip lines and developed new slip lines in directions approximately parallel to those produced by the repeated stress. In Fig. 22c there may be noted the development of slip lines in a second direction under the static elongation of 12 per cent. A study of the direction of the slip lines showed that they developed most numerously along two directions making angles of about

*"The Behavior of Single Crystals of Aluminum under Static and Repeated Stresses," (British) Aeronautical Research Committee, Reports and Memoranda No. 995. See also No. 1924.
"The Behavior of a Single Crystal of Alpha Iron Subjected to Alternating Torsional Stresses,' Proc. Royal Soc. A, Vol. 118, p. 498, (1928).
"The Behavior of a Single Crystal of Zinc Subjected to Alternating Torsional Stresses," Proc. Royal Soc. A, Vol. 123, p. 143, (1929).

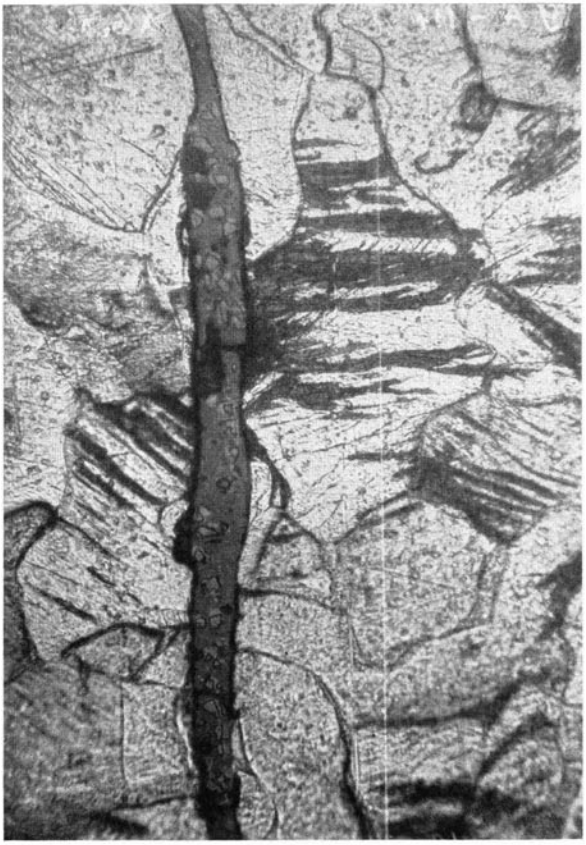


FIG. 15. SLIP LINES IN ARMCO IRON (x 650)
Reduced to two-thirds original size.
Specimen 9-117
Fractures after 1 896 700 cycles of reversed bending with a stress in outer surface of 22 800 lb. per sq. in.

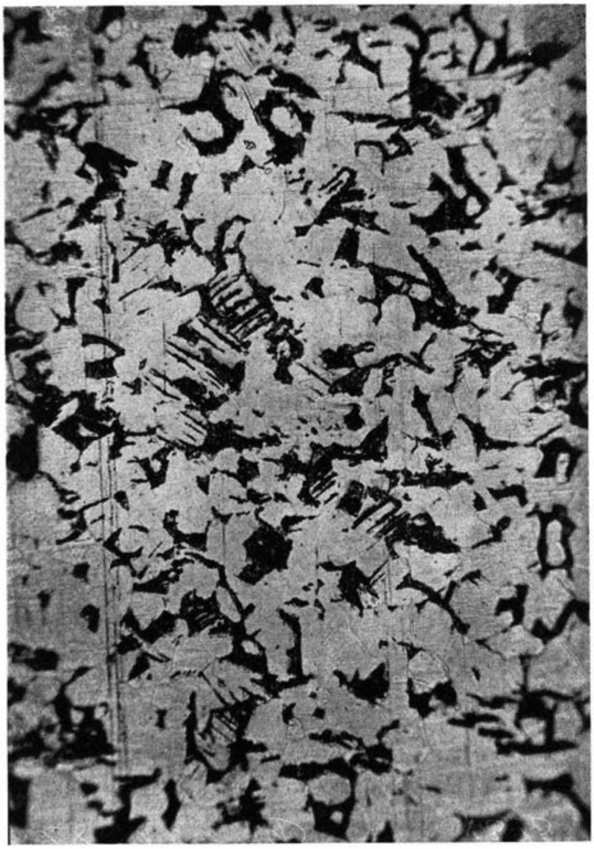


FIG. 16. SLIP LINES IN 0.20 CARBON STEEL, S.A.E. 1020 (x 390)

Reduced to two-thirds original size.

Specimen 28-117

Fracture after 10 681 600 cycles of reversed bending at 23 600 lb. per sq. in.
then 6 247 000 cycles of reversed bending at 25 200 lb. per sq. in.
then 3 610 000 cycles of reversed bending at 26 700 lb. per sq. in.
then 2 456 300 cycles of reversed bending at 28 200 lb. per sq. in.

FIG. 17. SLIP LINES IN CHROME-NICKEL STEEL, S.A.E. 3135 (x 1308)

Reduced to two-thirds original size.

Specimen 27-26

Fracture after 10 820 000 cycles of reversed bending at 38 400 lb. per sq. in.
then 10 376 000 cycles of reversed bending at 39 900 lb. per sq. in.
then 10 000 000 cycles of reversed bending at 41 500 lb. per sq. in.
then 10 544 000 cycles of reversed bending at 43 000 lb. per sq. in.
then 10 240 000 cycles of reversed bending at 44 500 lb. per sq. in.
then 1 777 500 cycles of reversed bending at 46 000 lb. per sq. in.

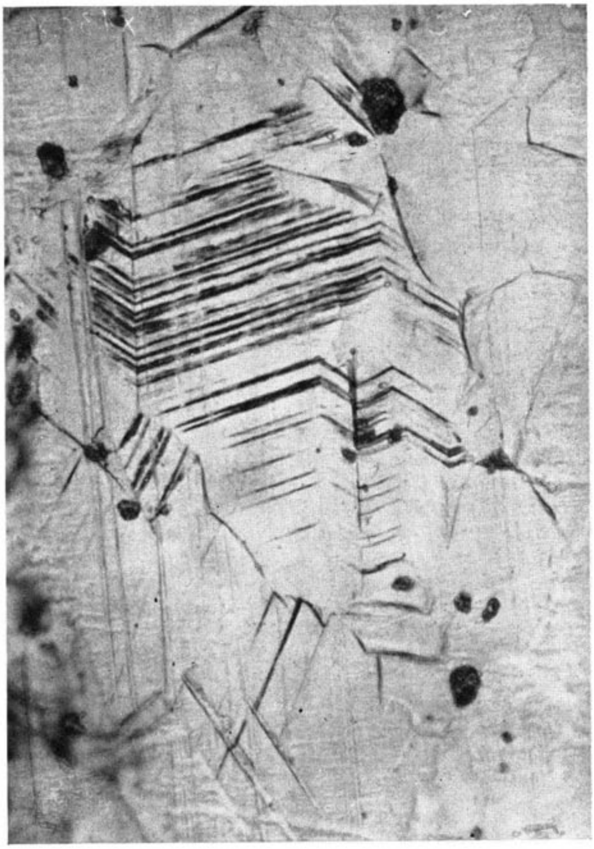


FIG. 18. SLIP LINES IN BRASS (x 1308)
Reduced to two-thirds original size.
Specimen 108-0
Fracture after 903 000 cycles of reversed bending at 22 900 lb. per sq. in.

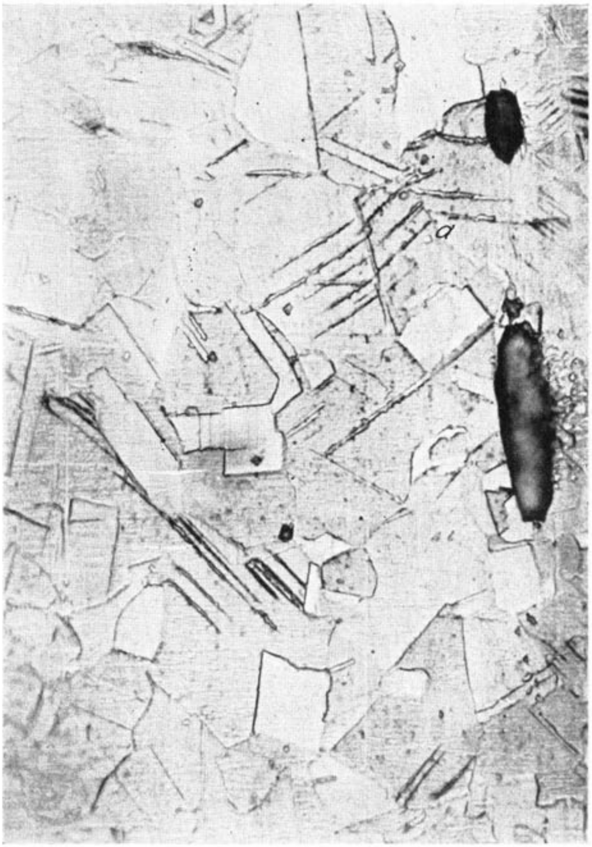
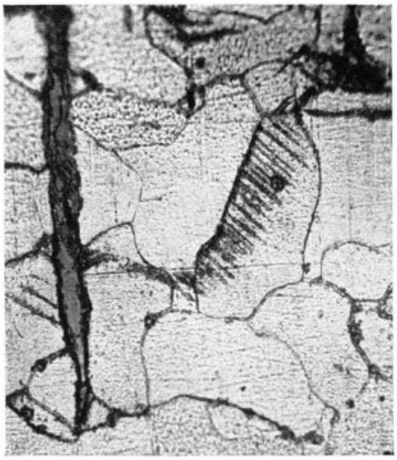


FIG. 19. SLIP LINES IN MONEL METAL (x 1308)
Reduced to two-thirds original size.
Specimen 115-52
Fracture after 405 600 cycles of reversed bending at 39 900 lb. per sq. in.
Note the double set of slip lines in crystalline grain *a*.

FIG. 20. SLIP LINES IN ARMCO IRON (x 650)
Reduced to two-thirds original size.
Specimen 9-112
Fracture after 1 896 000 cycles of reversed bending at 22 800 lb. per sq. in.
Note the double set of slip lines in the crystalline grain
near the central part of the figure.

FIG. 21. SLIP LINES IN DURALUMIN (x 390)
Specimen 130-39
Fracture after 1 737 700 cycles of reversed bending at 23 200 lb. per sq. in.
Note double sets of slip lines.



(a) Fatigue-Damaged Metal

(b) Fatigue-Damaged Metal After 6 per cent Elongation

(c) Fatigue-Damaged Metal After 12 per cent Elongation

FIG. 22. SLIP LINES IN ARMCO IRON BEFORE AND AFTER PLASTIC ELONGATION (x 390)

Reduced to two-thirds original size.

Specimen 9-117

Fracture after 1 896 700 cycles of reversed bending at 22 800 lb. per sq. in.

(a) Fatigue-Damaged Metal

(b) Fatigue-Damaged Metal After 6 per cent Elongation

(c) Fatigue-Damaged Metal After 12 per cent Elongation

(d) Fatigue-Damaged Metal After 20 per cent Elongation

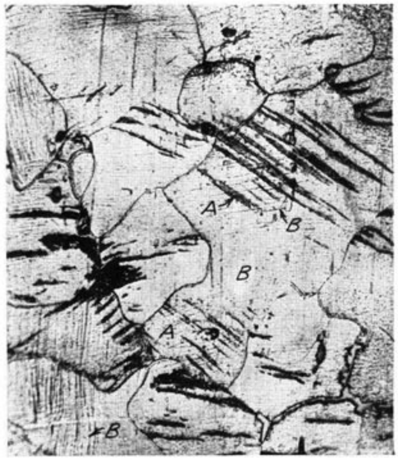
FIG. 23. SLIP LINES IN 0.20 CARBON STEEL BEFORE AND AFTER PLASTIC ELONGATION (x 312)

Reduced to two-thirds original size.

Specimen 28-0

Fracture after 10 506 000 cycles of reversed bending at 24 000 lb. per sq. in.
then 10 582 000 cycles of reversed bending at 25 400 lb. per sq. in.
then 2 103 000 cycles of reversed bending at 27 000 lb. per sq. in.
then 591 800 cycles of reversed bending at 28 600 lb. per sq. in.

(a) Fatigue-Damaged Metal



(b) Fatigue-Damaged Metal After Static Torsion

(c) Fatigue-Damaged Metal After a Second, Heavier, Static Torsion

(d) Fatigue-Damaged Metal After Two Applications of Static Torsion, then Elongation

FIG. 24. SLIP LINES IN ARMCO IRON BEFORE AND AFTER PLASTIC DEFORMATION (x 390)

Reduced to two-thirds original size.

Specimen 9-78

Fracture after 1 406 600 cycles of reversed bending at 22 800 lb. per sq. in. Slip lines *A* developed during repeated stress; slip lines *B* developed during static torsion; slip lines *C* developed during elongation.

(a) Fatigue-Damaged Metal (x 390)

(b) Fatigue-Damaged Metal After Static Torsion (x 1308)
Part shown in circle in (a).
Reduced to two-thirds original size.

(c) Fatigue-Damaged Metal After Static Torsion Followed by Elongation (x 1308)
Reduced to two-thirds original size.

FIG. 25. SLIP LINES IN 0.20 CARBON STEEL BEFORE AND AFTER PLASTIC DEFORMATION

Specimen 28-117

Fracture after 10 681 600 cycles of reversed bending at 23 600 lb. per sq. in.
then 6 247 000 cycles of reversed bending at 25 200 lb. per sq. in.
then 3 610 000 cycles of reversed bending at 26 700 lb. per sq. in.
then 2 456 300 cycles of reversed bending at 28 200 lb. per sq. in.

Slip lines *A* developed during repeated stress; slip lines *B* developed during static torsion; slip lines *C* developed during elongation.

(a) Fatigue-Damaged Metal

(b) Fatigue-Damaged Metal After Static Torsion

(c) Fatigue-Damaged Metal After a Second, Heavier, Static Torsion

(d) Fatigue-Damaged Metal After Two Applications of Static Torsion, then Elongation.

Fig 26. Slip Lines in Monel Metal Before and After Plastic Deformation (x 1308)

Reduced to two-thirds original size.

Specimen 115-52

Fracture after 405 600 cycles of reversed bending at 39 300 lb. per sq. in.

Slip lines *A* developed during repeated stress; slip lines *B* developed during static torsion; slip lines *C* developed during elongation.

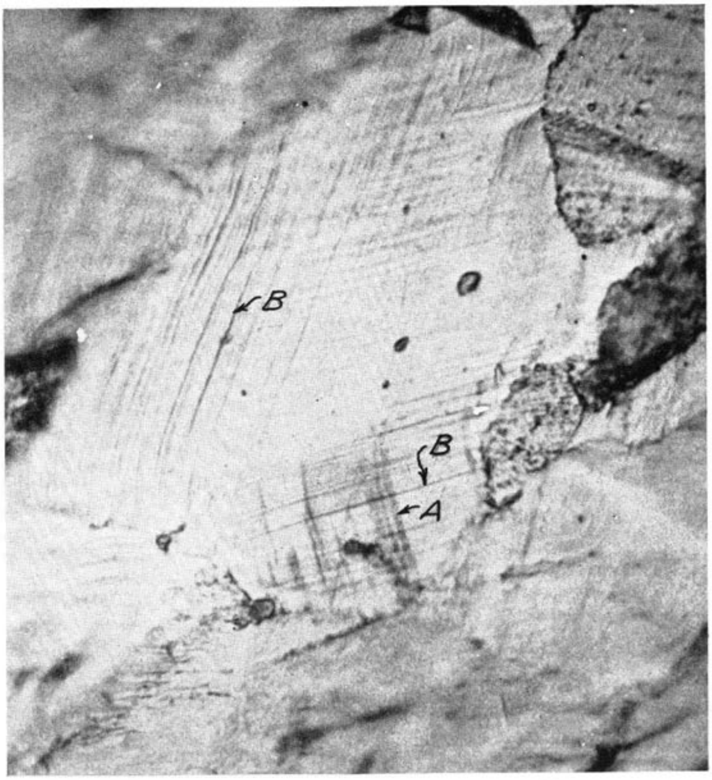


FIG. 27. SLIP LINES IN FATIGUE-DAMAGED BRASS BEFORE AND AFTER PLASTIC DEFORMATION BY TORSION (x 1308)

Specimen 108-52

Fracture after 642 cycles of reversed bending at 23 200 lb. per sq. in. Slip lines *A* developed during repeated stress; slip lines *B* developed during static torsion.

(a) Metal Subjected to Repeated Stress Below the Endurance Limit, Followed by Static Torsion

(b) Metal Subjected to Repeated Stress Below the Endurance Limit, Followed by Static Torsion and Elongation

FIG. 28. SLIP LINES IN ARMCO IRON SUBJECTED TO REPEATED STRESS BELOW THE ENDURANCE LIMIT, FOLLOWED BY PLASTIC DEFORMATION, TORSION AND ELONGATION (x 390)

Specimen 9-78

Slip lines *B* developed during static torsion; slip lines *C* developed during elongation. In this specimen no slip lines developed during repeated stress. It is of interest to note that the two sets of *B* slip lines do not seem to lie so nearly at right angles as is the case for the specimens of fatigue-damaged metal.

45 degrees with the axis of the specimen, that is, along the directions of maximum shearing stress. Gough's tests, to which reference has already been made on page 24, indicate that for a specimen made up of a *single* crystal the direction of slip is determined by the planes of atomic weakness in the space lattice. It seems reasonable to picture slip lines in a multi-grained piece of metal developing first in those grains in which the planes of atomic weakness in the space lattice coincide quite closely with the planes of maximum shearing stress. The fact that, under direct tensile loading, there are on any longitudinal section of a specimen two planes of maximum shearing stress at right angles to each other explains the appearance under increased elongation of a second set of slip lines approximately at right angles to the first slip lines developed in a grain.

Further evidence of the tendency of slip lines in a multi-grained specimen to form along lines of maximum shearing stress was given by a study of slip lines set up when specimens of the form shown in Fig. 8c were subjected first to fatigue tests and then to static torsion tests and static tension tests. Under static torsion the directions of maximum shearing stress would be parallel to and at right angles to the axis of the specimen, and at 45 degrees with the direction of maximum shearing stress developed in the static tension tests. The development of slip lines under such stresses is shown in Figs. 24 to 28, inclusive. In the figures, *A* denotes slip lines developed under cycles of reversed bending, *B* denotes slip lines developed under static torsion, and *C* denotes slip lines developed under static tension. It will be seen that there is a very general tendency towards parallelism between *A* slip lines and *C* slip lines with the *B* slip lines developing in two directions at right angles to each other and approximately at 45 degrees with the *A* lines and the *C* lines—that is, the directional relation of the three types of slip lines is approximately the same as that of the maximum shearing stresses set up by the different loadings.

It is worthy of note that the *A* slip lines, those developed under repeated stress, show a tendency to form broader bands than the slip lines developed under static loading. This suggests the gradual thickening under repeated stress of the thin plates of metal between slipping laminae; metal in which the atomic arrangement is disturbed.

In general, this study of slip lines gives support to the theory that slip in multi-grained pieces of metals, and therefore their elastic strength, depends chiefly on the magnitude and direction of the maximum shearing stress set up.

12. *Development of Fatigue Cracks.*—For the metals tested a very general tendency was observed for fatigue cracks to develop from slip lines or at least to follow the direction of slip lines. This is illustrated in the micrographs, Figs. 29 to 33, inclusive. The presence of cracks is made more evident if the specimen, after a period of repeated stress above the endurance limit, is subjected to static tension or static torsion. The static stress opens up any cracks. Figures 34 and 35, each of which shows two micrographs of the same area on a specimen, illustrate this point.

In some of the specimens tested (brass, monel metal, and duralumin) a crack appeared before any slip lines were observed, while in others (Armco iron and 0.20 carbon steel) many slip lines developed before a crack became visible. The early stages of development of a fatigue crack are shown for duralumin in Figs. 36 and 37, for brass in Fig. 38, and for monel metal in Fig. 39. In Figs. 37 (duralumin) and 39 (monel metal) two cracks are shown developing near each other.

The details of the process by which cracks are started are still a matter of speculation. Gough* pictures the cracks as starting from a wrinkling of the slipping surfaces, while Haigh† pictures the arising of a state of "triple tension," that is, tension along the three axes of principal stress, in the interior of the lamina of metal which is slipping. This state of "triple tension" is similar to the state of stress in the metal in the interior of a rapidly cooling sphere of metal where the relatively hot metal is pulled in all directions by the relatively cool metal on the surface. If the tensile stress is equal along the three principal axes of stress the shearing stress disappears, and with it the possibility of slip. In metal under "triple tension," when an atomic bond is broken presumably no new bond is formed (as in the case of slip), but fracture starts. As slip proceeds, it has been noted on page 24 that the thickness of the lamina of disturbed metal increases, as shown by the "thick" slip lines produced by repeated stress (see page 39); presumably the location where slip takes place is on the outer surfaces of thin laminae, the temperature is higher at the surface than at the center of a lamina, and a state of more or less perfect "triple tension" is set up.

In any event there is much to be learned about the starting of cracks in different metals before the marked differences for these different metals can be explained.

Once a crack is started it is easy to explain its spread by the fact of high stress concentration at its ends. Stress concentration and spread of cracks are discussed in some detail by Moore and Kommers.‡

When a slip or a crack occurs in a metal there is a tendency to relieve stress adjacent to the crack or the slip, and to throw stress back from the location where the slip or the crack occurs. On the other hand there is a distinct tendency to high localized stress at the ends of the crack or the edge of the region of slip. These two actions, one a strengthening action and the other a destructive action, may be pictured as playing opposing parts in the struggle of the metal to resist failure.

A considerable amount of slip may occur without starting a fatigue crack, as in Armco iron and 0.20 carbon steel; conversely, for some metals, such as duralumin, the first observed metallographic

*Gough, Hanson and Wright, "The Behavior of Single Crystals of Aluminum under Static and Repeated Stresses," Phil. Trans. Royal Soc. A, Vol. 226, pp. 1 to 20.

†Haigh, "Chemical Action in Relation to Fatigue of Metals," Read before (British) Inst. of Chemical Engineers, March 20, 1929.

‡Moore and Kommers, "The Fatigue of Metals," (McGraw-Hill Book Co.), Chapter IV.

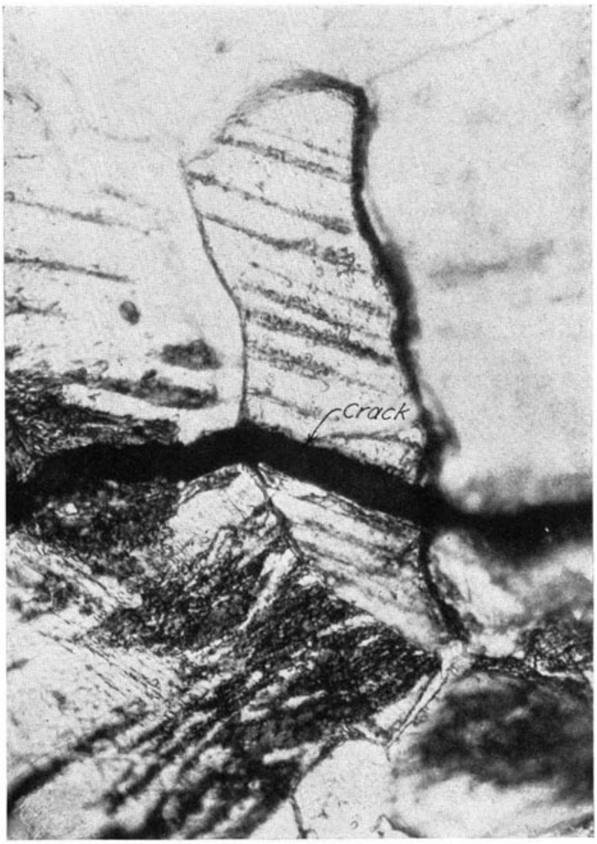
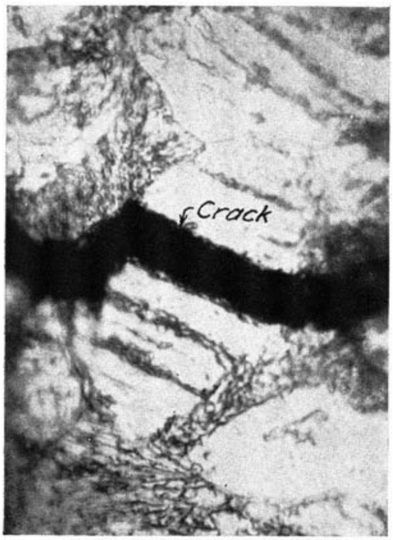


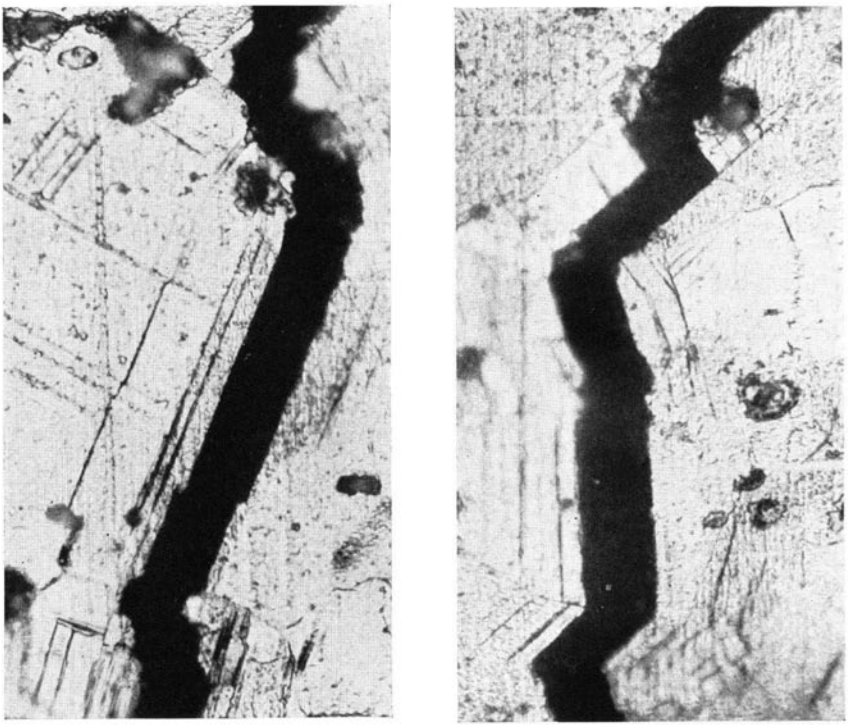
FIG. 29. FATIGUE CRACK IN ARMCO IRON (x 1308)
Reduced to two-thirds original size.
Specimen 9-117
Fracture after 1 896 700 cycles of reversed bending at 22 800 lb. per sq. in.
Note the crack following the direction of slip lines.



(a)

(b)

FIG. 30. FATIGUE CRACKS IN 0.20 CARBON STEEL, S.A.E. 1020 (x 1308)
Specimen 28-52
Fracture after 202 900 cycles of reversed bending at 35 500 lb. per sq. in.
Note the cracks following the direction of slip lines.



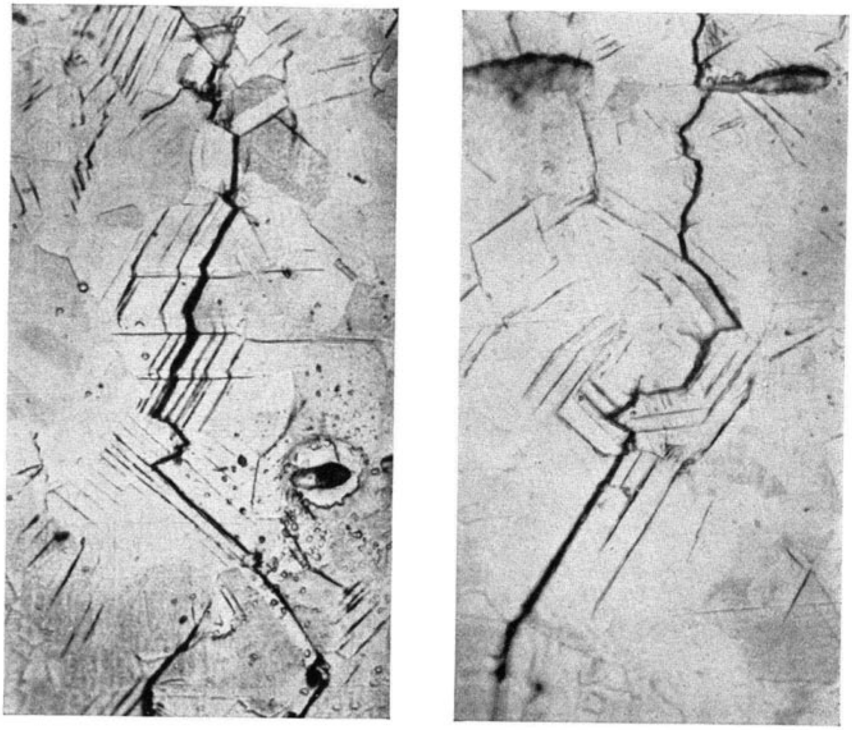
(a) (b)

FIG. 31. FATIGUE CRACKS IN BRASS (x 1308)

Reduced to two-thirds original size.

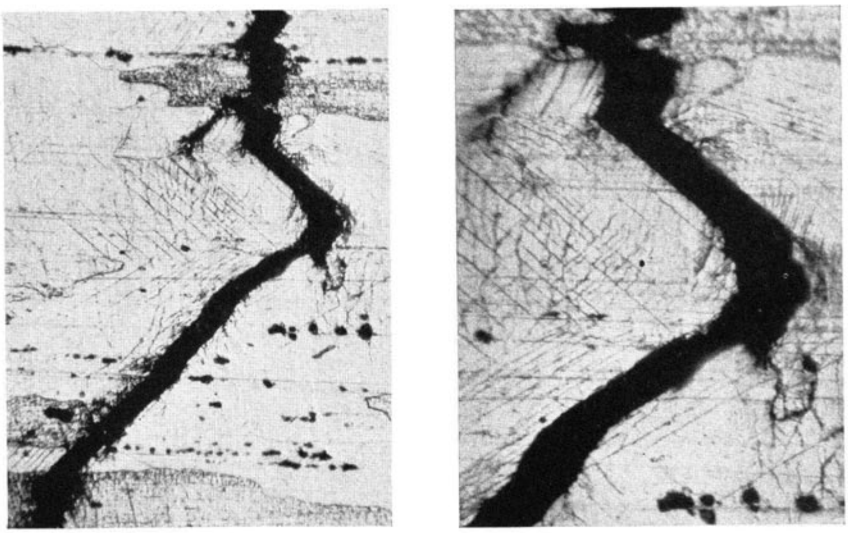
Specimen 108-52

Fracture after 642 000 cycles of reversed bending at 23 100 lb. per sq. in.
Note the cracks following the general direction of the slip lines.



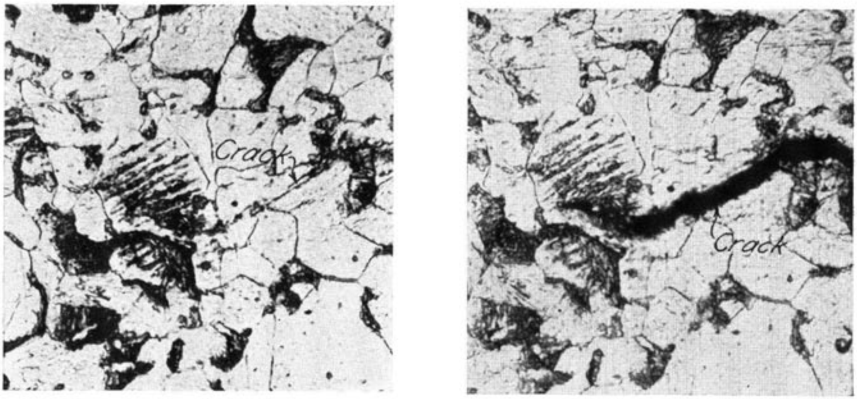
(a) (b)

FIG. 32. FATIGUE CRACKS IN MONEL METAL (x 1308)
Reduced to two-thirds original size.
Specimen 115-13
Fracture after 306 300 cycles of reversed bending at 40 500 lb. per sq. in.
Note the general parallelism of fatigue cracks and slip lines; in Monel metal the crack is detected before slip lines develop.



(a) (x 312) (b) (x 650)

FIG. 33. FATIGUE CRACKS IN DURALUMIN
Reduced to two-thirds original size.
Specimen 130-13
Fracture after 1 139 000 cycles of reversed bending at 25 700 lb. per sq. in.
Note the general parallelism of cracks and slip lines. In duralumin the fatigue crack is detected before slip lines develop.



(a) Fatigue-Damaged Metal

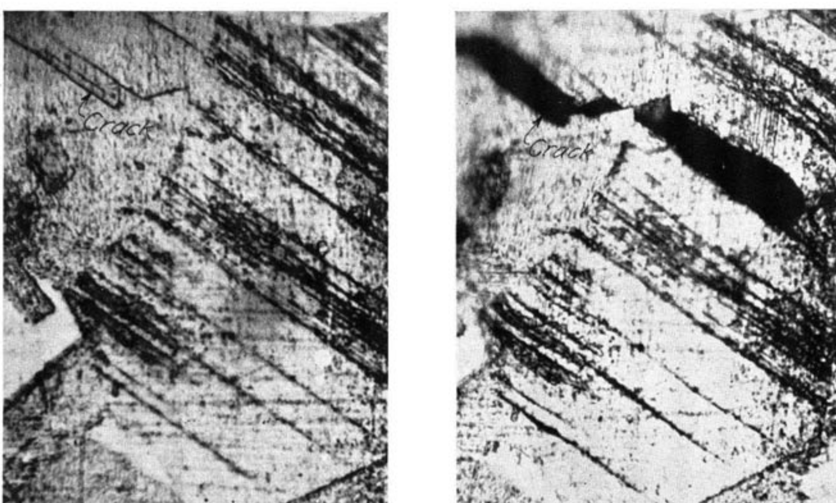
(b) Fatigue-Damaged Metal After 5 per cent Elongation

FIG. 34. DEVELOPMENT OF FATIGUE CRACK IN 0.20 CARBON STEEL BY PLASTIC ELONGATION (x 650)

Reduced to two-thirds original size.

Specimen 28-26

Fracture after 482 300 cycles of reversed bending at 27 600 lb. per sq. in.



(a) Fatigue-Damaged Metal

(b) Fatigue-Damaged Metal After Static Torsion

FIG. 35. DEVELOPMENT OF FATIGUE CRACK IN BRASS BY PLASTIC DEFORMATION IN TORSION (x 1308)

Reduced to two-thirds original size.

Specimen 108-52

Fracture after 642 cycles of reversed bending at 23 200 lb. per sq. in.

(a) (x 312)

(b) (x 650)

FIG. 36. EARLY STAGES OF DEVELOPMENT OF FATIGUE CRACKS IN DURALUMIN
Reduced to two-thirds original size.
Specimen 130-39
Fracture after 1 737 700 cycles of reversed bending at 23 200 lb. per. sq. in.

FIG. 37. DOUBLE FATIGUE CRACK IN DURALUMIN (x 390)
Specimen 130-39
Fracture after 1 737 700 cycles of reversed bending at 23 200 lb. per sq. in.
Note the double crack. This may either be two cracks or one crack which between the visible portions goes beneath the polished surface of the specimen.

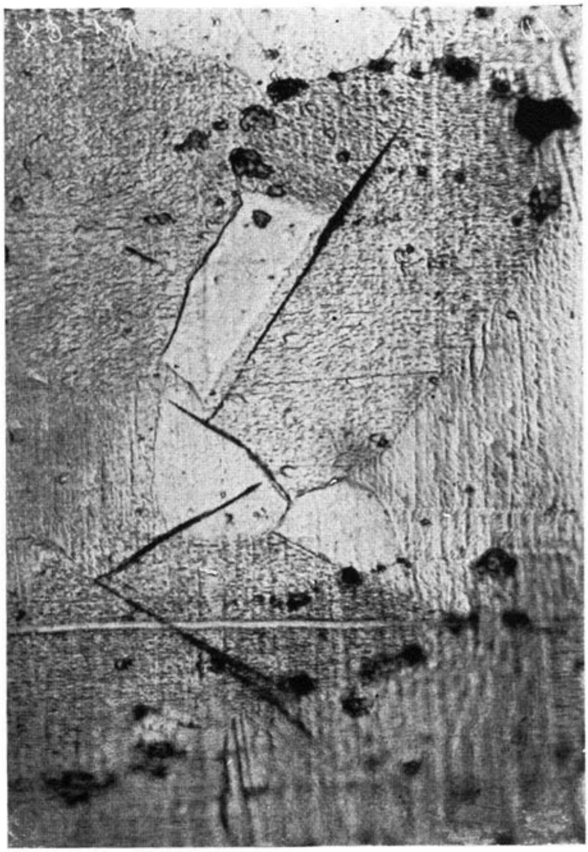
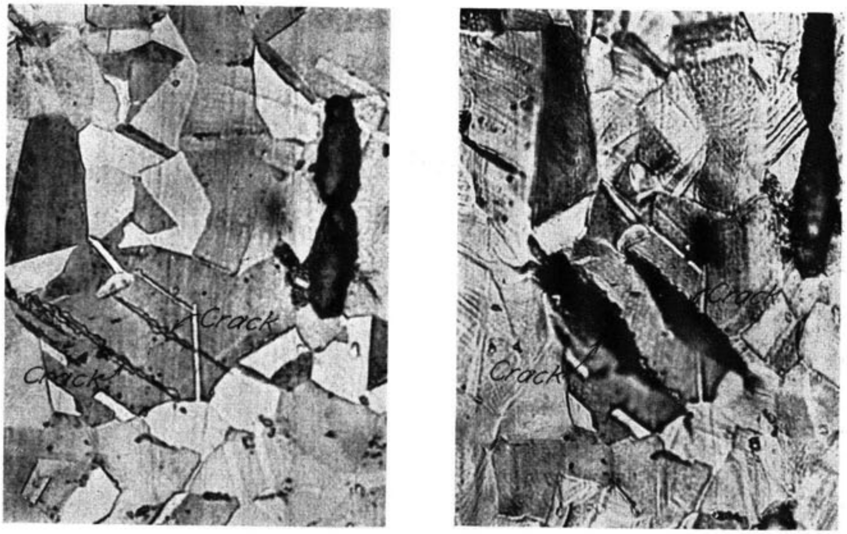


FIG. 38. EARLY STAGES OF DEVELOPMENT OF FATIGUE CRACK IN BRASS (x 1308)

Reduced to two-thirds original size.

Specimen 108-65

Fracture after 1 214 000 cycles of reversed bending at 20 800 lb. per sq. in.



(a) Early Stage of Fatigue Cracks in Fatigue-Damaged Metal

(b) Development of Fatigue Cracks and of Slip Lines by Elongation of Fatigue-Damaged Metal

FIG. 39. EARLY STAGE OF FATIGUE CRACKS IN MONEL METAL AND DEVELOPMENT OF CRACKS AND SLIP LINES BY PLASTIC ELONGATION (x 1308)

Reduced to two-thirds original size.

Specimen 115-65

Fracture after 1 144 500 cycles of reversed bending at 38 900 lb. per sq. in.

FIG. 40. FATIGUE CRACK AND SLIP LINES IN DURALUMIN (x 312)
Specimen 130-13
Fracture after 1 139 000 cycles of reversed bending at 25 700 lb. per sq. in
The slip lines developed after the fatigue crack became visible.

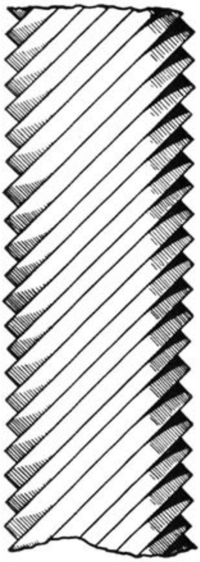


FIG. 41. FORMATION OF HARTMANN (LUEDERS) LINES BY SLIP

appearance of structural damage under repeated stress is a crack. However, after a crack starts in duralumin the sudden readjustment of stress in adjacent parts of the metal may cause slip lines to appear, as is shown in Fig. 40.

13. *Comparison of Behavior Under Stress of Single Crystals and of Multi-grained Pieces of Metal.*—The recent work of Gough* has thrown light on the behavior of single crystals under stress. The first occurrence of slip seems to be a function of the orientation of the atoms in the space lattice of the crystal. Slip first occurs along definite planes of the space lattice, and along these planes the resistance to slip is only a small fraction of the resistance of ordinary multi-grained metal. Fatigue cracks in single crystals, however they start, seem, however, to follow lines of maximum stress as they progress.

As a contrast to the behavior of the single crystal under repeated stress there may be considered the behavior of a multi-grained piece of metal under a single load. If the metal is at all ductile, and if the grains have been given no particular orientation by stress, either no fatigue damage is done, or it spreads but a little distance. The def-

*Gough, Phil. Trans. Royal Soc. A, Vol. 226, pp. 1 to 20. (British) Aeronautical Research Committee Reports and Memoranda No. 1024 and No. 1025, Proceedings Royal Soc. A, Vol. 118, p. 498 and Vol. 123, p. 143.

ormation of the metal is mainly by slip, and, in general, the slip occurs along the line of the maximum shearing stress, presumably occurring first in those grains whose planes of atomic weakness coincide fairly closely with the planes of maximum shearing stress. This is shown in an exaggerated form in Fig. 41. There is a tendency to produce wrinkles in the surface at fairly regular intervals, and the form of the surface disturbance depends on the average properties of the metal and the direction of the stresses rather than on the atomic arrangement of any single crystal.

The behavior of a piece of multi-grained metal under repeated stress seems to be a compromise between the two extreme cases of a single crystal under repeated stress and a multi-grained piece of metal under single loading. It seems to be reasonable to assume that there is a distinct tendency for slip and fracture to start in grains with unfavorable orientation. But the spread of such damage, and probably its start, is very much influenced by the strength of the surrounding grains with more favorable orientation of atoms, and by the strength of the irregular atomic arrangement of metal which makes up the grain boundaries. Moreover, repeated cycles of stress, in so far as they cause slip without cracks, tend to strengthen the metal. Cycles of repeated stress apparently have a tendency to orient the crystalline grains into a common direction of planes of maximum strength, although this tendency is by no means fully effective. Thus metal subjected to fatigue damage might be expected to act somewhat like a single crystal. Such general distortions in the directions of maximum shearing stress as are shown in an exaggerated form in Fig. 41 would be less likely to occur in metal subjected to fatigue damage than in undamaged metal, owing to the tendency of the partially oriented crystalline grains to fail along planes of maximum atomic weakness rather than along planes of maximum stress. This has a bearing on the formation of visible strain lines on the surface of metal under stress, which is discussed in the succeeding paragraph.

14. *Development of Hartmann (or Lueders) Strain Lines in Steel With and Without Fatigue Damage.*—When certain metals are stressed in tension beyond the yield point diagonal lines appear on the surface of the specimen which are known as Hartmann (or sometimes Lueders) lines. When the surface of the specimen is polished these lines appear to be due to a slight wrinkling of the surface. It seems as if there were a general distortion of the metal taking place, approximately along the direction of maximum shearing stress, and as if the distortion were taking place somewhat as shown in an exaggerated form

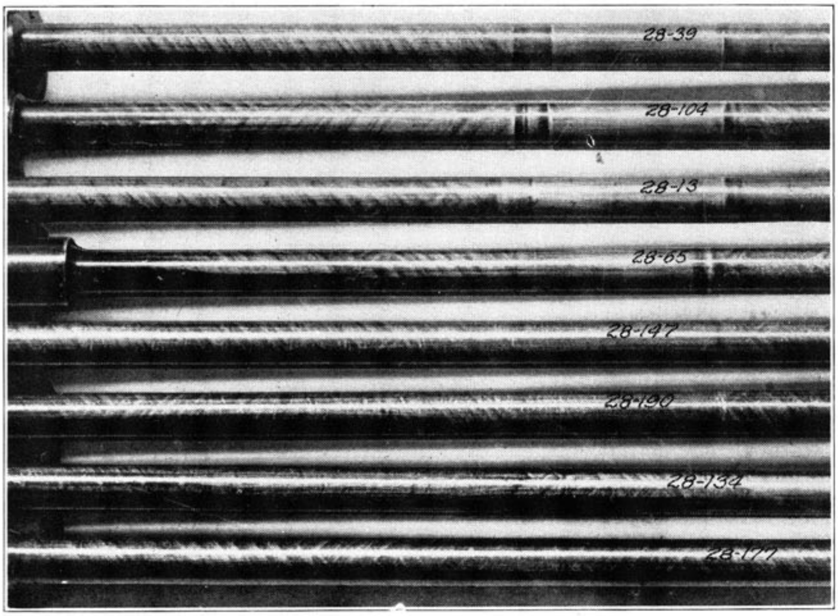


FIG. 42. HARTMANN (LUEDERS) LINES DEVELOPED IN TENSION SPECIMENS CUT FROM FATIGUE SPECIMENS

Specimen numbers shown in cut.

Specimens are tension specimens cut from fatigue specimens as shown in Fig. 8.

Material, 0.20 carbon steel.

in Fig. 41. These lines are most readily developed in annealed metal, in which, presumably, the atomic and crystalline arrangements have attained a state closely approaching equilibrium.

If any straining action tends to set up internal strains, especially internal strains oriented in some particular direction, or if such action has any tendency to move slightly the crystalline grains, or to distort the space lattice of individual grains, then it might be expected that these Hartmann lines would not be so readily produced on the metal.

Figure 42 shows the development of Hartmann lines on eight specimens of 0.20 carbon steel. The specimens were turned down to the shape shown in Fig. 8c from the unbroken end of a double fatigue specimen, as shown in Fig. 8a, so that one part of the tensile specimen had been subjected to cycles of alternating stress of considerable magnitude, and the remainder had been subjected to alternating stresses of small magnitude. The record of the stresses carried by the highly stressed part of each specimen will be found in Table 3. It will be noted that specimens 28-177, and 28-134, 28-190, both stressed below

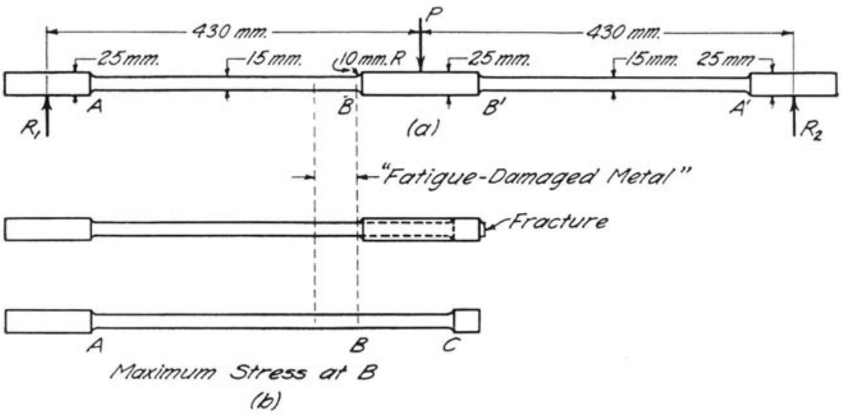


FIG. 43. SPECIMENS USED IN BUDAPEST TESTS

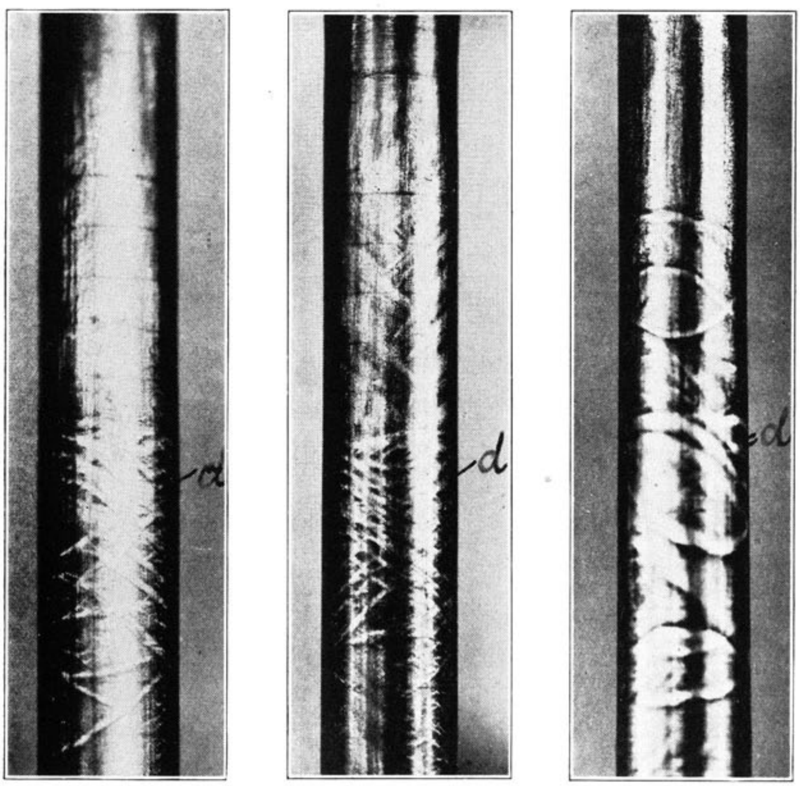


FIG. 44. SLOPE OF HARTMANN LINES IN FATIGUE-DAMAGED AND IN UNDAMAGED METAL—BUDAPEST TESTS

Material, 0.10 carbon steel tested by Dr. Ver in Budapest. *d* marks portion of metal which has been fatigue-damaged.

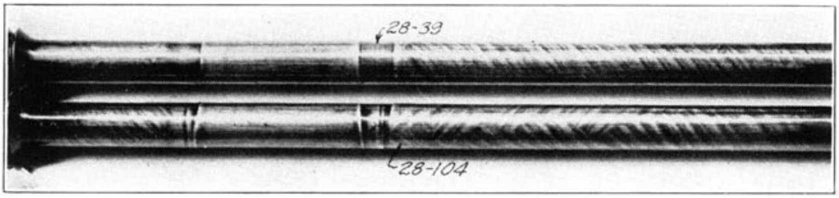
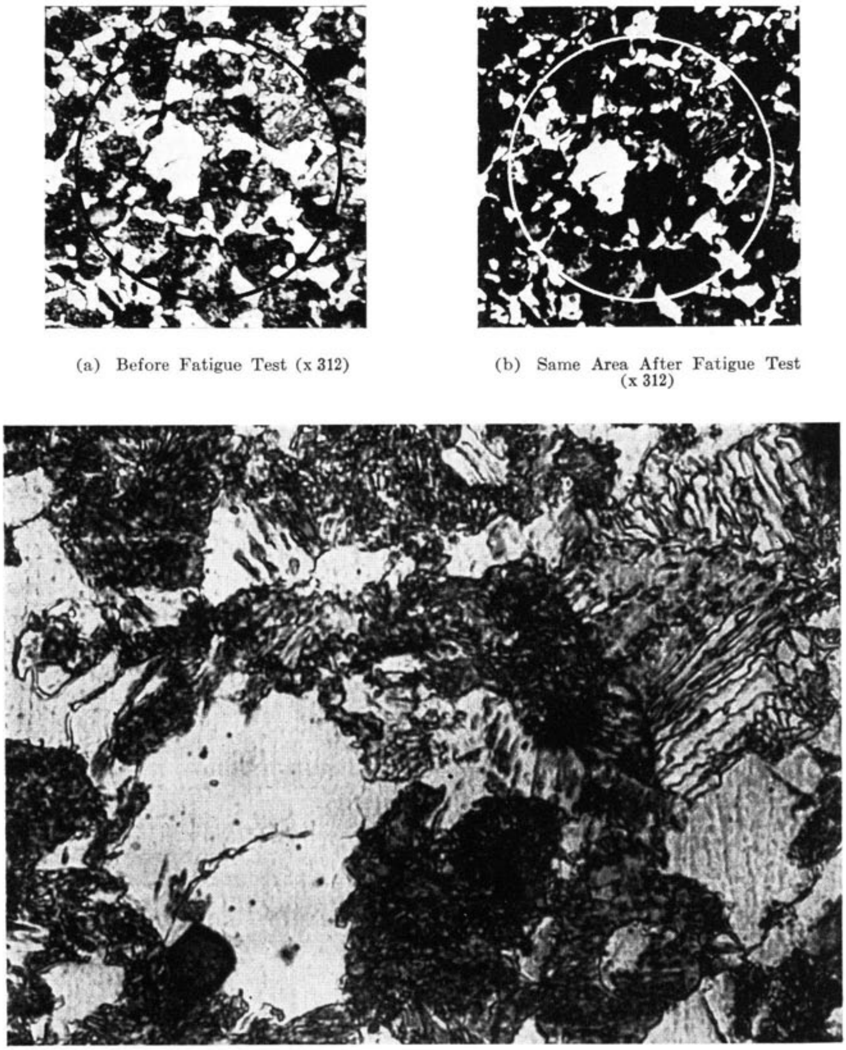


FIG. 45. SLOPE OF HARTMANN LINES IN FATIGUE-DAMAGED AND IN UNDAMAGED METAL—ILLINOIS TESTS
Specimen numbers shown in cut.
Specimens are tension specimens cut from fatigue specimens as shown in Fig. 8.
Material, 0.20 carbon steel.

the endurance limit in reversed flexure, show no marked difference in the development of Hartmann lines on the part subjected to alternating stress. For the other specimens, in which the reversed flexural stress was either above the endurance limit or quite close to it, Hartmann lines can be seen on the portion not subjected to heavy reversed stress, but those lines disappear on the portion subjected to cycles of reversed stress above the endurance limit. It will be noted that for specimens 28-147 and 28-190, in which the stress was very close to the endurance limit, the change in Hartmann lines is not so well marked as in specimens subjected to higher stresses.

Further evidence of the change of direction of the Hartmann lines is given in an article by Dr. Ver,* describing work done by him in the Mechanical Technological Department of the University of Technical Sciences in Budapest. The material used in his tests was steel with a carbon content of about 0.1 per cent. The specimen subjected to reversed flexure is shown in Fig. 43a. It is a double specimen with stress intensity increasing from A to B and A' to B'. The maximum fiber stress due to flexure is at the fillets B and B'. When one side of the specimen breaks a tension specimen is turned from the other (unbroken) side, as is shown in Fig. 43b. In this specimen the metal at A has been subjected to cycles of reversed bending stress of low intensity, and the magnitude of stress to which the metal has been subjected increases from A to a maximum at B, beyond which it is less than at B. Figure 44 shows the tensile specimens after being stretched 5 per cent. The part subjected to repeated stress above the endurance limit is at or near d in Fig. 44. As the intensity of repeated stress increases (from top to bottom of figure) it can readily be seen that the direction of the Hartmann lines changes and becomes more nearly perpendicular to the axis of the specimen. This tendency is shown

*Magazine of the Hungarian Materials Testing Association, Nov. and Dec., 1928.



(a) Before Fatigue Test (x 312)

(b) Same Area After Fatigue Test (x 312)

(c) Portion of Area Within Circle Shown in (a) and (b) After Fatigue Test (x 1308)

FIG. 46. APPARENT CHANGE OF CRYSTALLINE STRUCTURE OF CHROME-NICKEL STEEL DUE TO FATIGUE DAMAGE, REALLY DUE TO FRAGMENTATION OF CRYSTALLINE GRAIN

quite strikingly in Fig. 45, which shows some of the tensile specimens tested at the University of Illinois.

It seems that the action of cycles of reversed flexure above the endurance limit of the metal changed the internal strains, the internal crystalline arrangement, or the internal atomic arrangement of the metal so that the tendency for general slip to occur along a plane at 45 degrees with the axis of a tensile specimen was appreciably altered, and the plane of slip became more nearly parallel to the axis.

15. *Change of Form of Crystalline Grains Under Repeated Stress.*—The question whether under repeated stress the crystalline grains of metal suffer any appreciable change of form or position—whether any change goes on which might be called "crystallization"—has always been of great interest to the testing engineer. Herold* has shown that, using great care to have uniform etching reagents and uniform material, the microscopic appearance of steel of high manganese content, of nickel steel, and of chrome-nickel steel is markedly changed by repeated stress.

This question was studied for the chrome-nickel steel in the present investigation. Figure 46a shows the appearance of a spot on the chrome-nickel steel before it was subjected to cycles of reversed flexure, and Fig. 46b shows the same spot after the specimen had been subjected to many cycles of stress above the endurance limit. Apparently the white grains have shrunk and in some cases disappeared, while the dark grains have grown larger. Figure 46c shows the part of Fig. 46a and 46b enclosed in the circle, and it can be seen that the blackening of many grains in Fig. 46a is caused by the presence of a multitude of slip lines—in fact, the blackening of areas by slip lines has been observed by many metallographists.

Changes are caused in crystalline grains by repeated stress, but these changes seem to consist of fragmentation of crystals, breaking up of crystalline grains into laminae by slip, or, possibly alterations in the physical strength and resistivity to etching reagents, and are not, in general, changes which may be described as "crystallization" or "recrystallization." The results of the work of the present investigation in this respect have received confirmation from results of work done in the Fatigue of Metals Laboratory of the University of Illinois by Mr. S. W. Lyon, and as yet unpublished.

*Zeit. des Vereines deutscher Ingenieure, July 16, 1927.

V. Conclusions

16. *Summary of Conclusions.*—The following is a brief summary of work done in and conclusions to be drawn from the present investigation:

(1) This bulletin records the results of study of slip, fatigue cracks, and strain lines in specimens of the following metals: Armco iron, 0.20 carbon steel (S.A.E. 1020), chrome-nickel steel (S.A.E. 3135), stainless iron (Ascoloy), brass, monel metal, and duralumin.

(2) Fatigue tests were carried out using rotating-beam specimens. Each specimen had two turned down sections, each subjected to the same range of stress. When one side broke the other, although unbroken, evidently had been subjected to repeated stress sufficiently high to cause structural damage, to which the name "fatigue damage" is given. The unbroken part of the specimen presumably was "fatigue-damaged" along part of its length, but for the portion not turned down was undamaged. By turning down part of the undamaged portion of the specimen to the size of the fatigue-damaged portion there was formed a tension (or torsion) specimen which was available for studying the properties of metal with and without fatigue damage.

(3) The specimens of Armco iron and of 0.20 carbon steel showed a greater Rockwell "B" hardness for the fatigue-damaged portion than for the undamaged portion; the other metals tested showed either a very slight increase in hardness for the fatigue-damaged portion or a slight decrease.

(4) Except for the chrome-nickel steel and the 0.20 carbon steel the portions of the specimens in which fatigue damage had taken place showed a slightly higher yield point than the specimens from undamaged metal, but no estimate of the quantitative difference can be given from the test data.

(5) For the specimens of Armco iron, of 0.20 carbon steel, and of chrome-nickel steel the fatigue-damaged portions showed a markedly smaller reduction of area under plastic strain than did the undamaged portions. The specimens of brass showed the same result to a less degree; the specimens of duralumin and of monel metal showed no marked difference between portions with and without fatigue damage; and the specimens of stainless iron showed a *larger* reduction of area for the fatigue-damaged portions than for the undamaged portions.

(6) A study of the formation of slip lines during the tests indicates that for the metals tested slip tends to take place in the direction of maximum shearing stress.

(7) A microscopic study of the formation of fatigue cracks during the tests indicated a strong tendency for cracks to follow the direction of previously formed slip lines, or to appear in a direction in which subsequently slip lines were formed. For the Armco iron and the 0.20 carbon steel, slip lines formed abundantly before fatigue cracks became visible. For the brass, the monel metal, and the duralumin, fatigue cracks appeared before slip lines were visible. No microscopic study was made of the formation of fatigue cracks in specimens of the stainless iron or of the chrome-nickel steel.

(8) Specimens of 0.20 carbon steel showed marked differences in the development of Hartmann (or Lueders) lines under plastic stretch. The portions of the specimens in which fatigue damage had taken place showed no Hartmann lines, while such lines were abundant on the undamaged portions. At the zone dividing the undamaged portion without cracks from the fatigue-damaged portion, the Hartmann lines seem to change direction from approximately 45 degrees with the axis to approximately 90 degrees. This indicates to the writers that either the cracks themselves or the orientation of strained crystalline grains along the specimen tend to hinder the general slipping throughout the whole body of the specimen in the direction of maximum shearing stress.

(9) A study of the apparent change of form and size of the crystalline grains of the chrome-nickel steel specimens under repeated stress leads to the conclusion that the apparent change is due to the fragmentation of grains into laminae by slip, and that there is no evidence of any change due to repeated stress which can be called "crystallization" or "recrystallization."

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